RAPID™
Transforming Process Industries

Transforming the Process Industries through Modular Chemical Process Intensification

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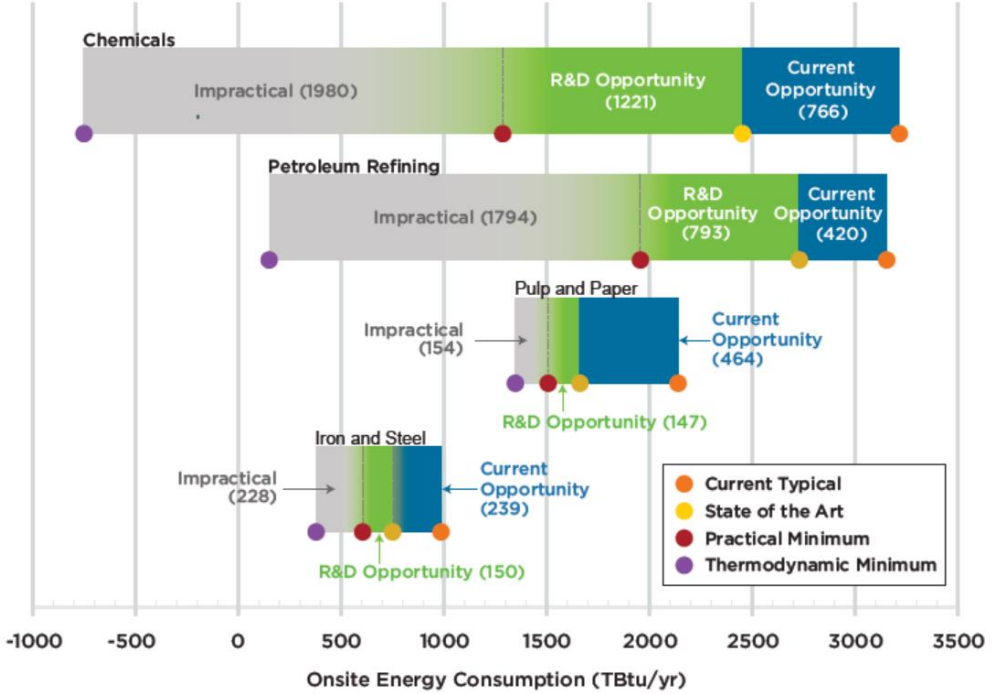
Energy & the Chemical Process Industries

- Manufacturing sector accounts for a quarter of the total US energy use
- Process industries are the largest consumers in the sector
- AMO recognized potential for MCPI
- Process industries lacked the MCPI tools, knowledge, experience, leadership, and convening body needed to transform the industry



–DOE AMO Energy Bandwidth Studies
https://www.energy.gov/eere/amo/energy-analysis-data-and-reports

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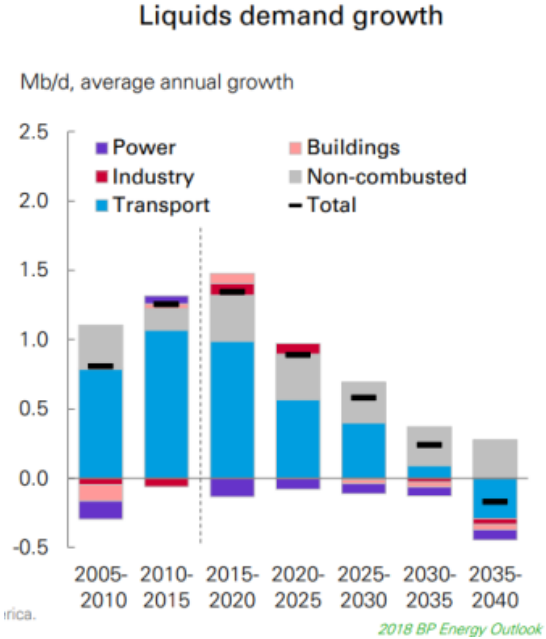
External Forces Creating Pressure for Change

Shifts in Supply/Demand



BP

Increase Pressure on Operational Footprint

Singapore carbon tax would hit refiners, help renewables

REUTERS FEBRUARY 20, 2017 / 8:55 PM

Advances in Adjacent Technologies

GE

Rise of Inexpensive Renewable Power

RAPID – Who are we?

RAPID™ Transforming Process Industries

Manufacturing USA Institute

- $150 million, 5 year public-private partnership between DOE and AIChE

RAPID Members

AIChE The Global Home of Chemical Engineers

U.S. DEPARTMENT OF ENERGY Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

- 87 member institutions
  47 Companies, 30 Universities,
  10 National Labs & Non-profits

RAPID Impact

- *Build Community*
- *Drive Thought Leadership*
- *Educate students and professionals*
- *Fund and manage R&D projects*

Premier

University of Pittsburgh, ExxonMobil, SIEMENS, Auburn University, DOW, Georgia Tech, Lubrizol, SRNL Savannah River National Laboratory, Oregon State University, University of Delaware, SoCalGas, Iowa State University

Choice

NC State University, Linde, Shell, Texas A&M, University of Minnesota, 3M Science. Applied to Life., The University of Texas at Austin, University of South Carolina, The University of Alabama, Tennessee Tech, West Virginia University, Braskem

Industrial Enabling

FS Induction Food Systems, Raytheon Technologies, Koch Modular Process Systems, DuPont, Chemstations, Shepherd, Compact Membrane Systems, AVEVA, gti, Sironix Renewables, Flint Hills Resources, U.S. Clean Water Technology, Captis Aire, InnoSepra, Optimation, Rockwell Automation, HTRI, Davis, Owens Corning, Ascend Performance Materials, JM, aspentech, Matric, Nalas Engineering Services, Inc., GORE, VPE

Academic Enabling

Stony Brook University, Missouri S&T, Washington State University, VCU, University of Arkansas, University of Michigan, Carnegie Mellon University, University of Arizona, University of Illinois, GSI, Cornell Energy Systems Institute, Rensselaer, Rutgers, UConn, WPI, KU Kansas

Non-Profit & National Lab Enabling

CISTAR, SwRI Southwest Research Institute, Argonne National Laboratory, NREL National Renewable Energy Laboratory, National Energy Technology Laboratory, Pacific Northwest National Laboratory, INL

Affiliate

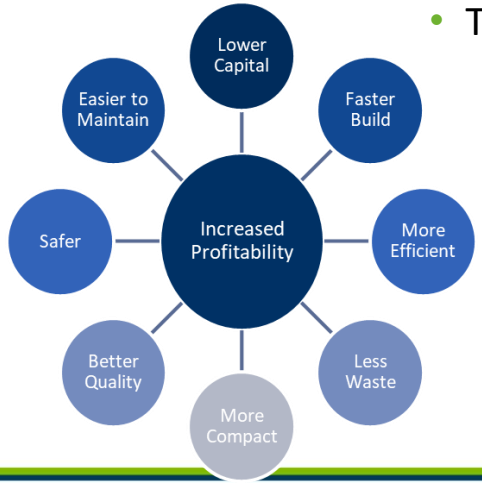
appti, Artisan Industries Inc., NobelClad, Michigan Technological University, STENCo, Dioxide Materials, microflowcvo, aircela, AGEIAS, FLOWID

Modular Chemical Process Intensification (MCPI)

Modular Processing

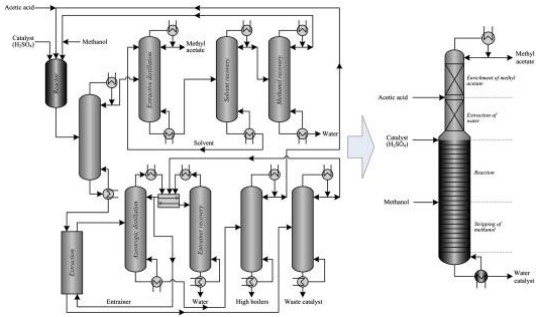
- Rethinking systems to enable flexible, **distributed manufacturing**
- Shift from **bigger is better** paradigm to **small, modular** paradigm
- Transition from volume scaling to **numbering up**

MCPI

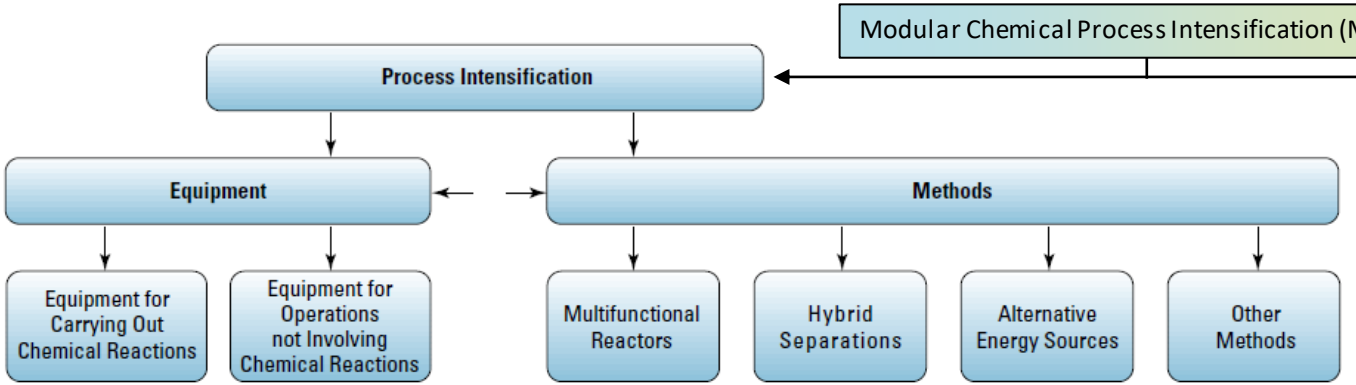


Process Intensification

- Rethinking processes to dramatically **improve performance**
- Shift from **unit operations** paradigm to **integrative** paradigm
- Transition from **batch to continuous**



MCPI Taxonomy



Examples

- Spinning Disk Reactor
- Static Mixer Reactor (SMR)
- Static Mixing Catalysts (KATAPAKs)
- Monolithic Reactors
- Microreactors
- Heat Exchange (HEX) Reactors
- Supersonic Gas/Liquid Reactor
- Jet-Impingement Reactor
- Rotating Packed-Bed Reactor
- Static Mixers
- Compact Heat Exchangers
- Microchannel Heat Exchangers
- Rotor/Stator Mixers
- Rotating Packed Beds
- Centrifugal Adsorber
- Reverse-Flow Reactors
- Reactive Distillation
- Reactive Extraction
- Reactive Crystallization
- Chromatographic Reactors
- Periodic Separating Reactors
- Membrane Reactors
- Reactive Extrusion
- Reactive Comminution
- Fuel Cells
- Membrane Absorption
- Membrane Distillation
- Adsorptive Distillation
- Centrifugal Fields
- Ultrasound
- Solar Energy
- Microwaves
- Electric Fields
- Plasma Technology
- Supercritical Fluids
- Dynamic (Periodic) Reactor Operation

Examples

Gas compression	Gas-to-Liquids
Chloralkali	Distillation

Gaps / Opportunities

- Understanding risks, cost, RAM
- Module Standardization
- Flexibility of assets
- Sensors, controls, automation

Adapted from Stankiewicz and Moulijn, *Chemical Engineering Progress*, ©2000 American Institute of Chemical Engineers.

MCPI Opportunities

Opportunities

- Modular platforms to streamline deployment and reduce costs
- More efficient reactor and separations technology

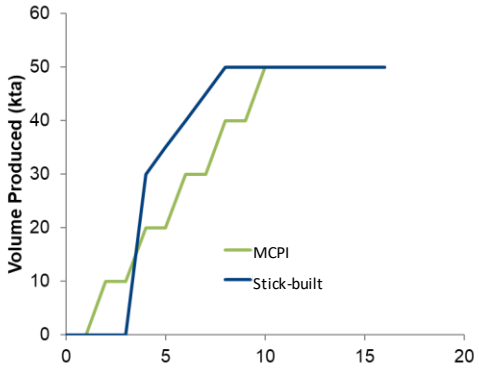
But, *technology development is needed*

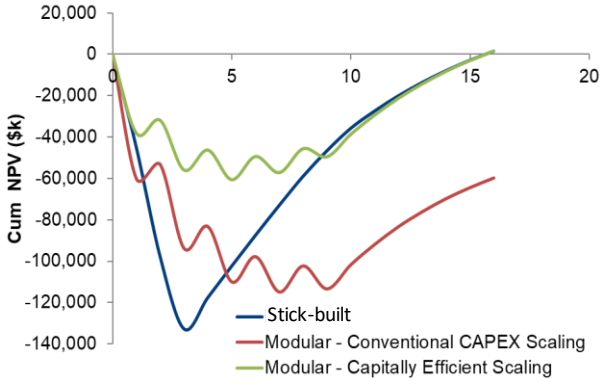
Critical Gaps	Potential PI/Modular Solutions
Efficient Batch to Continuous Conversion	Modular systems for scalable continuous production
Reaction Chemistry	Novel reactor designs, alternative energetics (induction, plasma, microwave, sono/electrochemistry)
Separations/Heat Transfer	Acoustic/ultrasound, enhanced membranes
Process design tools	Process synthesis and multi-scale modeling for PI equipment

Modeling the Total Cost of Ownership for Scaling-Up via MCPI

Develop real world case studies and supporting models to understand true costs to scale in number versus traditional volume scaling.

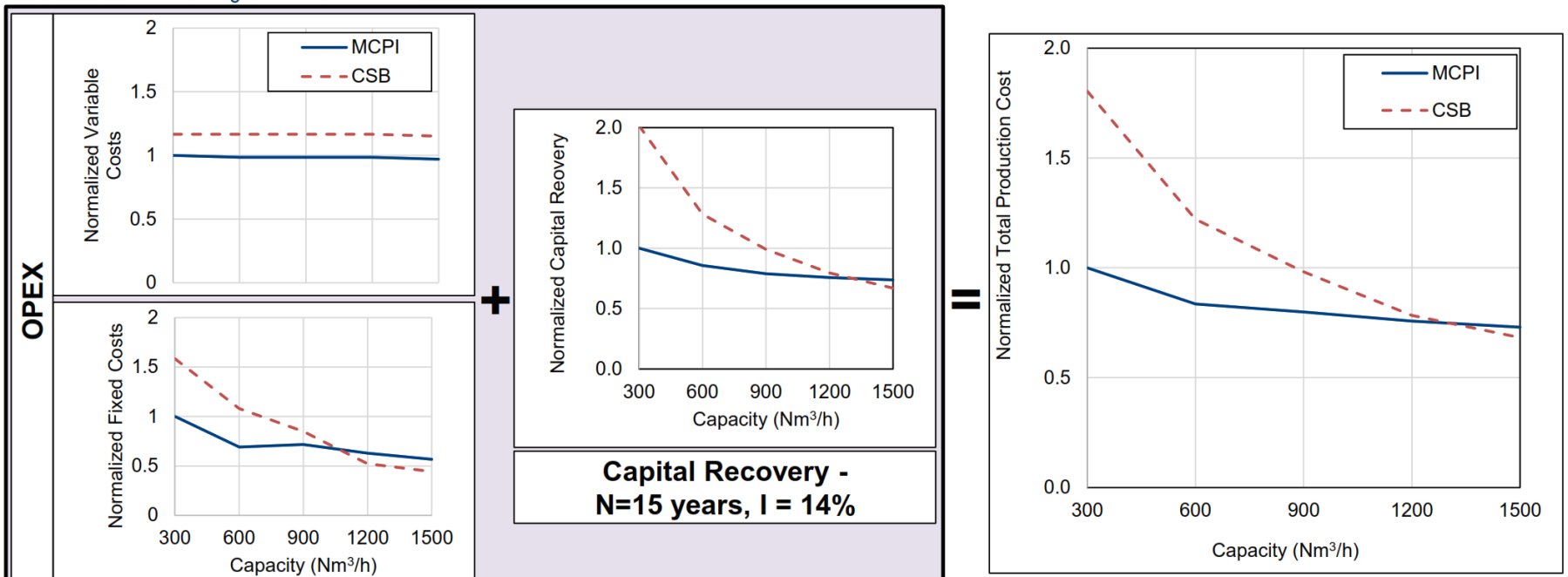
- Provide case studies to provide insight into **decision rationale** for using MCPI within specialty chemical and distributed chemical markets
- Compare total cost of ownership (TCO) and net present value (NPV) for MCPI and conventional "stick-built"
- Determine CAPEX and OPEX **correction factors** for modularization, PI and numbering up





Case Study #3 - Distributed Commodity Production

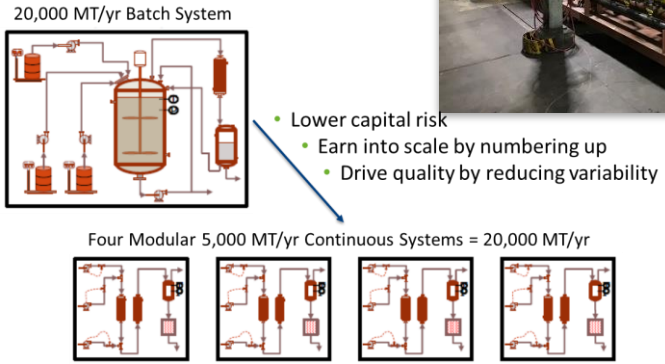
Total Production Cost Comparison for MCPI and CSB



- Total production cost for MCPI is relatively lower up to 3 trains
- Findings align with the case study partner's deployment strategy of numbering-up to 3 trains, thereafter moving to a mid-sized or a large-sized CSB plant

Modular Platform for Continuous Manufacturing of Specialty Chemical

Modular process developed and commercialized in under 20 months with 90% lower CAPEX, >30% lower OPEX, and improved product quality.



Technology	Conversion of succinimide dispersants production process from ***batch to continuous*** in compact, modular processing units
Base Case	Current manufacturing site within Lubrizol utilizing current state-of-the-art batch technology
Model Deployment Cost Reduction	**~80% lower capacity cost** • Process efficiencies • Modular standardized size • Much smaller equipment • Equipment utilization efficiency • Proven through pilot unit experience

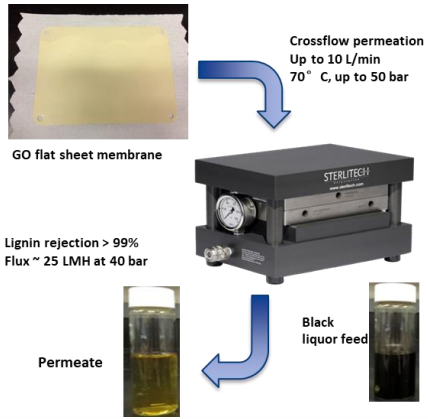
Novel Separations

Novel Membranes for Low Energy Separations of Complex Aqueous Systems

Graphene oxide membrane for separations of high ionic strength multiphase liquids, with kraft black liquor as primary test case.

Georgia Institute of Technology

appti



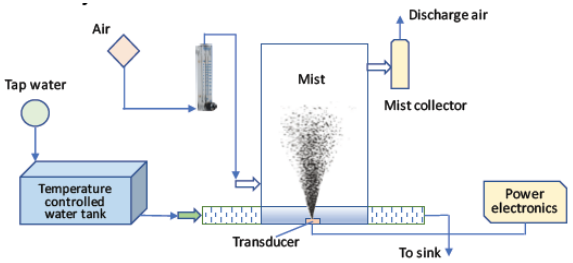
Power Ultrasound for Nonthermal, Non-equilibrium Separation of Ethanol/Water

Low energy ethanol separation from aqueous solution using power ultrasound avoiding azeotrope limitations.

ILLINOIS

FLINT HILLS resources

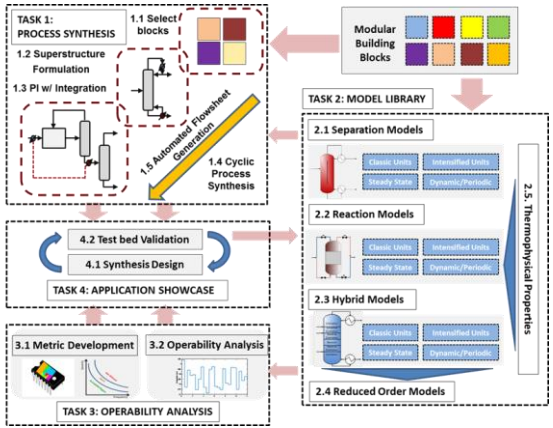
Carnegie Mellon University



Advanced Systems Modeling

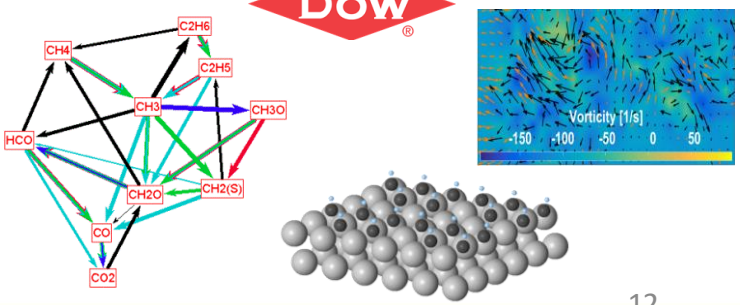
SYNOPSYS – Synthesis of Operable Process Intensification Systems

Process synthesis modeling toolbox for analyzing and predicting the optimal production system for existing and new processes.



RAPID Reaction Software Ecosystem

Multiscale chemical reaction network modeling tools including physical property and reaction thermochemistry estimation to reaction network prediction and analysis.



MCPI for Reprocessing – Some Ideas

- *Process Intensification (PI)*
  - Technologies used in reprocessing use PI ideas *already (e.g. solvent extraction)*
  - Batch-to-continuous process for pyro-processing (electrochemical)
  - Combination of operations/phenomena in one unit (e.g. reactive separation)
- *Modularization*
  - Distributed reprocessing close to the source (reactor)
    - Minimize transportation (cost, safety, etc.)
    - Reduce regulatory burden
  - Number-up vs. scale-up
    - Module standardization and replication
- *Combination of PI and Modularization*
  - MCPI combines the benefits of PI and modularization
  - Combined benefits are larger than additional improvements – *synergistic effects*

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Questions?

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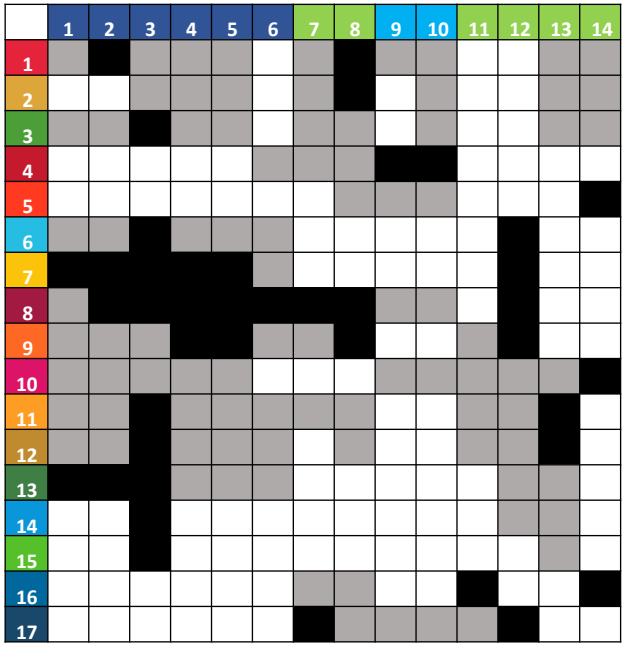
Addressing Sustainability



RAPID Metrics